Renewable and Sustainable Energy Reviews 38 (2014) 164–171

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Methods to estimate the industrial waste heat potential of regions – A categorization and literature review

Sarah Brueckner [a,c,*], Laia Miró [b], Luisa F. Cabeza [b,1], Martin Pehnt [c,2], Eberhard Laevemann [a]

[a] ZAE Bayern, Walther-Meißner-Str. 6, 85748 Garching, Germany
[b] GREA Innovació concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain
[c] Ifeu GmbH, Wilckensstraße 3, 69120 Heidelberg, Germany

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form
27 March 2014
Accepted 28 April 2014
Available online 14 June 2014

Keywords:
Waste heat potential
Resource estimation
Exhaust heat

ABSTRACT

To investigate heat demand, one can usually base the estimation on sales data for the energy carriers or even use the data directly. This works for companies, regions, towns and sectors (e.g., industry or domestic sector). But for the waste heat produced by the industry it is not that simple: waste heat is an output value, which neither costs nor earns any money and it is therefore seldom measured or reported. In this paper, different methods to estimate the excess heat of industrial production within a region are categorized and compared. Besides the obviously necessary distinction between theoretical, technical and economic potential, the authors suggest categorization of the methods in three dimensions: study scale, data collection and approach/perspective (bottom up vs. top down). Following this schematic, previous regional waste heat studies are reviewed. Studies focusing on single sectors or companies are not considered in this review, as well as studies estimating the heat demand. As a result it can be seen that the available data are the driving force in the choice for the used estimation method. For general factors, the resulting waste heat potential ranges between 5 and 30% of the energy demand of the industrial sector of a region. Once derived, key figures are often reused in other studies for other countries. Therefore, more data and a thorough meta study of the available figures are desirable.

Contents

* Corrsponding author. Tel.: +49 89 3294 4234; fax: +49 89 3294 4212.
E-mail addresses: sarah.brueckner@zae-bayern.de (S. Brueckner), lcabeza@diei.udl.cat (L.F. Cabeza).
[1] Tel.: +34 973003576; fax: +34 973003575.
[2] Tel.: +49 6221 4767 0; fax: +49 6221 4767 19.

http://dx.doi.org/10.1016/j.rser.2014.04.078
1364-0321/

1. Introduction

In the light of preventing global warming and therefore reducing CO_2 emissions, the way we use energy to produce our goods has to be looked upon. Industries worldwide use 38% of the final energy or more than 58,600 TWh (2010) [1]. That is why the energy consumption of industrial processes should be reduced as far as possible. But even optimized systems will release waste heat; waste heat that in some cases can still be used in other processes with a lower temperature demand. Despite this direct reuse there is also the possibility to use the industrial waste heat to produce cold, heat or electricity by applying different exhaust heat technologies, as it is being done for power plants. Industrial waste heat has, for a long time, been neglected, since it is lot more fragmented than power generation. Still, as the industrial sector uses 38% of the end energy, the potential is considerable and should be investigated. The largest amounts of waste heat in industries are usually found in basic metals, chemical industry, non-metallic minerals, food and tobacco, and pulp and paper.

In this paper, first different methods to estimate the waste heat potential of a region are categorized. Second, previous studies are reviewed according to the presented characterization. The presented paper focuses on studies that consider the whole industry within a certain region or country, not single sectors or companies. Those studies usually focus on energy-intensive sectors or technologies and their applicability. For example, De Beer [2] investigated the waste heat in the board and paper industry in the United Kingdom (UK), while Fleiter et al. [3] did the same for Germany. Dittmar et al. [4] evaluated data centers, which are a very promising waste heat source as they increase in number and improvements in efficiency are outnumbered by increased size and capacity. Neelis et al. [5] approximated the waste heat in the petrochemical industry. There are also many studies on waste heat from power production plants (e.g., [6]). [7] focuses on industrial furnaces and their heat recovery potential.

This paper focuses on studies that consider the whole industry within a certain region or country, rather than just single sectors.

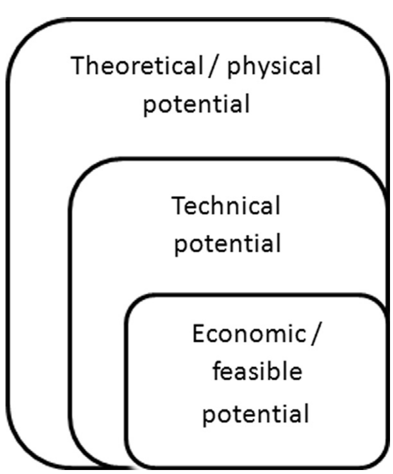

Fig. 1. Types of potential, graph based on [9–11].

It is independent of technological constraints. In addition, only exhaust heat that is bound in an air or gas stream is considered.

Studies estimating the heat demand are also not considered. It is important not to mix up the often found studies of the heat demand of a sector with the waste heat: the energy used does not equal the released waste heat since energy remains in the product or is released diffusively.

1.1. Definition of waste heat and its potential

1.1.1. Definition of waste heat

In this paper, waste heat is considered as all forms of heat (latent as well as sensible) that escape a system are not the purpose of the system. Heat from combined heat and power plants is therefore not considered. Sources for waste heat in industries can be single machines or whole systems that release waste heat into the environment. These sources include furnaces, waste water from washing, drying or cooling processes, and also refrigeration systems, motors or the exhaust air from production halls [2]. Waste heat can be released either diffusively as radiation or convection at a surface or through a heat carrier medium like exhaust gas, cooling fluids or steam [8]. In the presented studies the diffusive waste heat is not considered.

1.1.2. Definition of waste heat potential

When considering different methods to estimate the waste heat potential it is necessary to first distinguish which potential type is considered. In general, three different kinds of potentials should be distinguished: the theoretical or physical potential [9], the technical potential and the economically feasible potential [10] (Fig. 1). The theoretical potential only considers physical constraints: only heat above ambient temperature that is bound in a medium, etc. Thus, heat that is released diffusively, for example by radiation, is not assessed. In this case, whether or not it is possible to extract that heat from the carrier fluid or whether there is any way of using it, is not considered. These constraints define the technical potential. This potential therefore depends on the technologies used. Technical constraints are, for example, the minimum temperature to allow the operation of a system, temperature losses due to heat transfer, etc. The economic point of view is considered in the economic potential. This is often referred to as feasible potential as well. Financial parameters like energy prices, interest rates and payback periods are considered.

1.2. Obstacles to using waste heat

Financial and regulatory constraints are very common obstacles for new technologies, so they are for waste heat technologies as well. In addition, making profit from their waste heat is not the main business case for manufacturing companies. But as the International Energy Agency [12] points out, there are also significant technical challenges and limitations to excess heat recovery. These technical challenges are sometimes the main barriers to the implementation of industrial excess heat recovery

Table 1
Barriers of waste heat utilization weighted by experts [8].

Barriers	Possible solutions	Relevance[a]
Technological barriers		
No nearby heat sink		High
For in-house use		High
For heat transfer to third parties	Building heating pipes, heat transport	High
No information about heat sinks nearby	Waste heat exchange (information portal)Look for neighboring businesses such as in industrial areas	High
Time discrepancy Generation of heat/demand	Using heat in a different way such as power generation or feeding the power grid, storage	Medium
Temperature levels		
Too low	Using heat pumps	Medium
Too high	Mixing in steam or similar, cascading the use	Low
Production process		
Disturbance of the operation		High
Production reliability		High
During the conversion phase		Medium
Ongoing		
Boiler reliability	Redundant boilers	Medium
Financial and administrative barriers		
Availability of investment funds	Subsidies, loans	Medium
Priority of the core business	Use of service providers, waste heat contracting	Medium
Too high rate of return expectations	Information about life cycle costs	High
Uncertainty of the economic future		
For the investing company		High
For potential heating customers		Medium
Administrative effort for approval, execution and accounting		Low
Information		
Lack of business knowledge and personnel	Information campaigns and technology specific training courses for selected target groups	Medium
Research costs too high	Development investment calculation tools for consulting engineers and facility operators in the workplace	Low

[a] Emphasis determined by 30 experts during a workshop in April 2010.

projects. Table 1 shows a list of obstacles weighted by experts according to their relevance as well as possible solutions.

A significant amount of excess heat has to be available in the form of high temperature exhaust or byproduct gases. From a variety of processes, these gases contain corrosive materials and particulates, making them difficult to capture and recover as an energy resource.

When implementing waste heat recovery technologies, elimination of infrequent shutdowns and physical site constraints of space, proximity of heat recovery and usage areas are also problems to consider.

2. Characterization of different methods

Previously, different methods have been categorized either by their accuracy or by their data collection: Blesl et al. [11] differentiate them by accuracy and suggest three different methods to estimate the waste heat potential or heat demand: they suggest a rough method, using few statistical data, a medium precise estimate, with more detailed literature data and coefficients, and last a high precision method, with measured data. Pehnt et al. [2] distinguish between methods based on efficiency factors, questionnaire or measured data.

In general there are three perspectives to consider when classifying methods: the scale of the study, the way the data were acquired (survey or estimation) and the approach followed (top-down or bottom-up) to gain the result. The latter is only relevant for estimations, as surveys are always bottom-up.

2.1. Study scale

From this point of view, whether a single company is investigated, a neighborhood, a town, a region or a whole country is distinguished.

2.2. Data acquisition

Two general approaches in data acquisition should be distinguished: whether the data are estimated or surveyed. Surveyed data could either be measured data or collected via a questionnaire, official reports or voluntary online databases. Unless the data are measured, however, they might in reality be estimated as well. For considering estimated data there are efficiency factors and energy factors: the first is based on the input energy of the system, the second can be based on different values like number of employees or sales, correlating to the company size. Estimated data are usually more precise, but they are also more time-consuming to obtain. In “Wärmeatlas Baden-Württemberg” [11] different techniques for data acquisition were compared: between estimating the heat demand for a single company using energy factors based on company type and process-based efficiency estimations and no discrepancy was detected. For the process-based estimation mass flows, heat capacities, temperature levels and efficiency factors were used. A different and more precise result could, according to their study, only be obtained by measuring the data at the company. These values differed from the earlier one by a factor of four. However, as [13] explains, it is not easy to measure in high temperature facilities. Measurements in furnaces can easily be disturbed, for example, by radiation.

2.3. Approach: bottom-up or top-down

The most common distinction for methods is between top-down and bottom-up models. Here the direction from which the problem is approached is considered: aggregating single case studies to a general result is considered a bottom-up approach. Using general results (for example, efficiency factors) for a specific problem characterizes a top-down approach. Surveys are always bottom-up approaches, as there cannot be general surveys. Estimations on the other hand can be either top-down or bottom-up

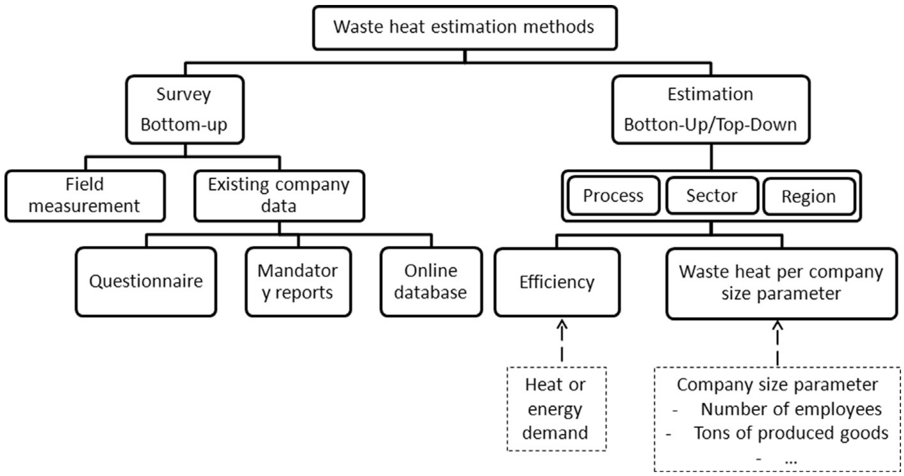

Fig. 2. Classification of methods.

approaches; they depend on the study scale: estimating the waste heat of a company based on the efficiency of each process is a bottom-up approach. Considering the process, however, it is a top-down method. Surveys usually lack the lowest investigation level and can only be found for study scales of sectors or regions. Since for estimation the study scale distinguishes between bottom-up and top-down models, its consideration is more important there. The often found rules of thumbs from experts are usually top-down estimations in the form of efficiency factors (e.g., "20% of the input energy can be recovered as waste heat").

A summary of the different approaches to estimating the industrial waste heat potential is given in Fig. 2.

Besides these theoretical classifications, in literature mixed forms can be found as well, where top-down estimations are validated bottom-up, a representative survey sample extended by an estimation, etc. However, for the sake of a classification this is not relevant.

3. Review of the applied methods in literature

Studies found in literature can be categorized according to the above-presented scheme. Nevertheless, sometimes it is not straightforward to which category a study has to be accounted, since different methods are mixed. Except for combined bottom-up/top down approaches, which are accounted for in a separate section, the studies are categorized by what appeared to be their main methodology. As mentioned above, waste heat potentials can be investigated in different scales: for companies or processes, industrial sectors or countries and regions. This literature review focuses on estimations for countries and regions.

3.1. Bottom-up survey

3.1.1. Questionnaire

An example of a survey study is a Norwegian study from 2009: Enova SF published a study on the industrial waste heat potential for Norway [14]. Enova SF is a publicly funded Norwegian state company from the *Ministry of Petroleum and Energy*. It was founded in 2001 to support more sustainable generation and consumption of energy, as well as to provide information [15]. For this study companies from food sector, wood processing (including paper production), chemical, cement and construction, aluminum, and iron industry sectors were considered as well as some companies with extremely high energy consumption like oil processing companies and waste incineration plants. In total, four waste incineration plants and 72 companies were investigated. These companies cover 69% of the total final energy consumption of the industrial sector in Norway. They discovered a waste heat potential of 19.4 TWh/y for heat above 25 °C. The temperature distribution of this waste heat is shown in Table 2. This study is a bottom-up approach carried out by a survey. How the surveyed data were obtained in the companies was not stated.

Table 2
Waste heat in Norway by temperature [14].

Temperature range	TWh/y	Percentage
> 140 °C	7.2	37
60–140 °C	3.1	16
40–60 °C	5.8	30
25–40 °C	3.3	17
Total	**19.4**	**100**

3.1.2. Mandatory reports

Bonilla et al. [16] and Lopez et al. [17] estimated the industrial waste heat potential of the industry in the Basque country (Spain) in 1996 and 1997, respectively. They differentiated the results by carrier medium (e.g., gas stream, solids or steam) and distinguished eight different temperature levels: above 1200 °C, 1200–800 °C, 800–400 °C, 400–200 °C, 200–120 °C, 120–80 °C, below 80 °C, and others. The studies are based on data of 260 [16] and 290 [17] companies respectively, summarized in the EVE data base (Ente Vasco de la Energia, Basque Government's energy agency). According to [17], 40.5% of the industrial energy demand is released unused as waste heat. They found that most waste energy is carried by gas streams (33%) and solids (27%). [16] found a very similar distribution of the waste heat: gas streams (32%), followed by solids (27%) and steam (16%). Nevertheless, since heat is very difficult to recover from solids, for further analysis only liquids, gas and vapor are considered as a carrier medium. They calculated the waste heat potential in the Basque country to be 51×10^6 GJ/y or 14 TWh/y. Most of this potential (23%) is in the 80–120 °C temperature range, second most (21%) above 1200 °C, and 19% between 400 and 800 °C. Since they used the single company data sets to determine the waste heat potential, this approach is a bottom-up method. The used data were not directly surveyed by them but instead by the EVE. Since the waste heat potential in the study is only restricted by the carrier medium, it is a theoretical potential.

3.1.3. Online waste heat platforms

No part of the above-presented schematic is online waste heat platform, since it does not quantify the waste heat in a region. It is rather a more practical approach in case a thorough estimation of the waste heat potential is not necessary. The main aim is not to quantify, but to connect different players by visualizing heat demands and sources. Therefore, it is in the companies' own interest to feed their data into these data bases. The existing data might therefore be more accurate than any external estimation, but not all companies are considered. Examples can be found in Thuringia (Germany) [18] Bavaria (Germany) [19], Saxony (Germany) [20], and the Netherlands [21].

3.2. Estimations

3.2.1. Bottom-up estimation

As an alternative to surveying data, estimations can be used. [22] used this method in 2004 to estimate the waste heat potential in the US. They derived efficiency ratios for single machines, processes and aggregated those to loss coefficients of sectors. These numbers were based on expert judgment, literature values and pilot projects. The focus of the work was the energy-intensive sectors like the chemical industry, oil refinery, wood processing, iron and steel, food processing, mining, and cement.

Ten years earlier, in 1994, Boddy et al. [23] used a similar approach, also for the US, stating ratios of the thermal input energy into a process that can be regained at which temperature (e.g., oven gas: 27% of the input energy at 361 °C). For certain industries such values are given per ton of produced goods: per ton of melted glass $0.7 \cdot 10^6$ MJ/t at 140–160 °C and $1.9 \cdot 10^6$ MJ/t at 160–200 °C. These data, however, were based on literature values from 1985 and earlier.

Another more recent study for the US using a similar approach was performed in 2008: the US Department of Energy in the Industrial Technologies Program (nowadays Advanced Manufacturing Office) published the estimated calculation per year in the US of exhaust gas waste heat losses in different applications: glass industry, cement kilns, iron and steel manufacturing, aluminum melting, and metal casting melting furnaces [24]. For that, assumptions based on previous literature are used depending on the process: production, exhaust temperature, energy consumption, etc.

For Baden-Württemberg, one of the federal states of Germany, two studies were conducted estimating the waste heat potential [11,25]. Both distinguished three different temperature levels (low temperature <100 °C, medium 100–500 °C and high temperature >500 °C). Blesl et al. [11] did a first estimation for four cities within Baden-Württemberg in 2008 based on literature values and empirical data. The highest waste heat potential was found in Rottweil with 14.9 GWh/y due to a foundry there that releases approximately 10 GWh/y. A more thorough approach was carried out later in 2012 by the same university department, estimating the waste heat potential based on case studies for each sector [25]. The latter showed a waste heat potential for Baden-Württemberg of approximately 8 TWh/y (1267 GWh/y <100 °C, 215 GWh/y at 100–500 °C, 6645 GWh/y >500 °C). Some sectors, however, like the chemical industry, are not stationed at all in this state. The investigated potential is an economic potential since the evaluated case studies were cases of economically successful usage.

Another estimation was done for the UK by McKenna et al. [26,27]: a technical usable potential from 10–20 TWh/y for the British Industry was evaluated. This estimation is based on emission data from the "UK National Allocation Plan for the EU Emission Trading Scheme," estimating the energy consumption. The waste heat was divided into five temperature levels (<100 °C, 100–500 °C, 500–1000 °C, 1000–1500 °C, >1500 °C) and homogenous sectors. Temperatures above 1500 °C can only be found in high-temperature processes as, for example, melting iron or steel. For each sector, the technical extractable waste heat was estimated. If no data were available, an average of 5–10% was assumed. This is based on the assumption that 80–90% of the input energy is used within the designed process. 50% of this waste energy is assumed to be technically recoverable. The biggest potential was discovered to be in the 100–500 °C range in the iron and steel industry, chemical, aluminum and the non-metallic mineral sector. The method was developed by McKenna et al. [27] and used as well in [26] and based on Hammond et al. [28] who only differentiated three temperature levels though. In a later study [29], the temperature range between 100 and 500 °C was split further, however, with similar results (37–73 PJ of waste heat).

Generally it has to be said that in bottom-up approaches it is hard to distinguish between expert judgment on single processes and, for example, estimations based on literature values since both are on a rather fine level.

3.2.2. Top-down estimations

The studies from [14,22] were combined and used to estimate the waste heat potential for Germany in 2010 by Pehnt et al. [8]. The evaluated energy factors for the different sectors and efficiencies were transferred, thus applying a bottom-up approach for the estimation. For Norway, the reference temperature the factors were based on was 0 °C. Based on these factors, for Germany a waste heat potential of 88 TWh/y above 140 °C was found and 44 TWh/y in the 60–140 °C range. In the highest temperature range, 42% of the waste heat potential was found to be in the iron sector.

A similar approach was followed by Ammar et al. [30], who used the results from Boddy et al. [23] to estimate a waste heat potential for the US. This top-down approach estimates 14.5 TWh/y at below 100 °C and 23.01 TWh/y of excess heat between 100 and 400 °C in UK.

In the Ecoheatcool project [31,32] the heat and cold demand in Europe were investigated. This project was part of the European Commissions' Intelligent Energy Europe program, from 2005 till 2006 [33]. The Ecoheatcool project was carried out by Euroheat & Power, a pan-European district heating association [34]. To evaluate the waste heat potential for all 32 European states the energy factors derived in a Swedish study [35] were applied to the other countries. For example, from oil refineries 0.6% of the input energy can be retrieved as waste heat; for paper 2.4%, in the chemical industry 12.2%, and in the mineral sector 2.9%. For all 32 states the waste heat potential was estimated as 1106 PJ/y or 307 TWh/y. This, however, is an economically feasible potential.

A special type of top-down estimation is experts making an estimation based on their experience: for Germany for example, Glatzel et al. [36] estimated that 40% of the industrial process heat can be regained as waste heat. Applying this factor leads to a waste heat potential of 1000 PJ/y or 280 TWh/y, respectively. In their guideline for waste heat usage in communities ("Leitfaden zur Abwärmenutzung in Kommunen") the Bavarian State Department for Environment estimates 20–30% of the total input energy (oil, gas, electricity, etc.) to be recoverable as waste heat. Since these values are based on experience rather than scientific studies, they are presented separately here.

3.2.3. Input value: heat demand estimations

When efficiencies are used to estimate the waste heat, heat demand estimations are necessary as input parameters. In contrast to the company parameters, which can easily be surveyed, heat demands are estimated using very similar methods. Although these are not within the focus of the paper, some examples are

presented here, to prevent confusion: for example, [31] estimated the European heat market. Three different temperature levels are distinguished: low temperature heat below 100 °C, medium temperature between 100 and 400 °C, and high temperature heat demand above 400 °C. They based their estimation on a study by AGFW (Germany District Heating Association) and evaluated a heat demand of 6530 PJ/y in 2003 for the EU15 states: 43% above 400 °C, 27% at 100–400 °C and 30% at low temperatures < 100 °C.

The heat demand was estimated using an energy demand factor normed to the companies' employees for different sectors. The study did not focus only on producing companies but considered other sectors such as trade and service sector as well. They first used the three different temperature levels mentioned above in [31] as this is later based on the factors developed in this study. The evaluated heat demand in Germany was found to be 1822 PJ/y.

Blesl et al. [11] estimated the heat demand for the industry in Baden-Württemberg, a federal state of Germany, by calculating energy demand factors per employee for different companies and per mass unit of produced good for different processes. The total heat demand of the industry was estimated at approximately 32 TWh/y.

Nevertheless, the energy used by an industry or a certain sector within an area does not equal the released waste heat: energy remains in the product or is released diffusively. Therefore efficiency factor has to be applied to the required energy to calculate the amount of waste heat per unit of input energy.

3.2.4. Combined top-down and bottom-up

Besides the categorized methods, there are also mixed approaches as, for example, combined bottom-up and top-down approaches. These are often found when either data are collected, energy figures derived and then transferred to a different region or extrapolated to larger scale; or when the potential is estimated in a top-down approach and then validated by samples, thus including a bottom-up part.

The first approach was used in Germany in 2002. In [37] the waste heat potential was estimated using a waste heat to input energy ratio for different industrial sectors. These figures were developed based on data from the city of Duisburg and then transferred to the whole state of North Rhine-Westphalia (NRW). In the evaluation of the waste heat two different temperature levels for its usage (and thus the reference temperature) were considered: 70 and 120 °C. For NRW this leads to a waste heat potential of ~14 TWh/y at 70 °C and 7 TWh/y at 120 °C.

Statistics Sweden [35,38] has developed a key figure – excess heat delivery per used fuel – for companies in each SNI group (Swedish Standard Industrial Classification, based on European NACE Code). Since the figures were developed to evaluate the potential use of waste heat in district heating systems, only

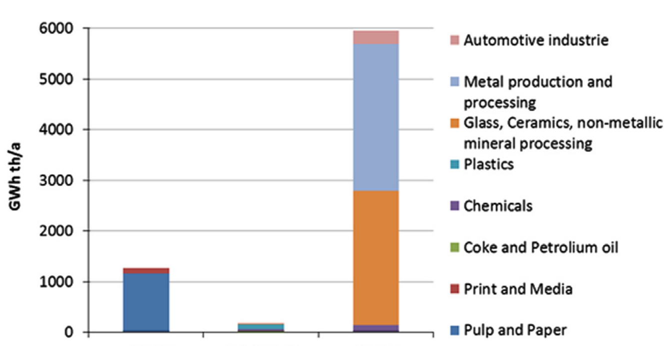

Fig. 3. Waste heat quantity in Baden-Württemberg per temperature and sector, based on [25].

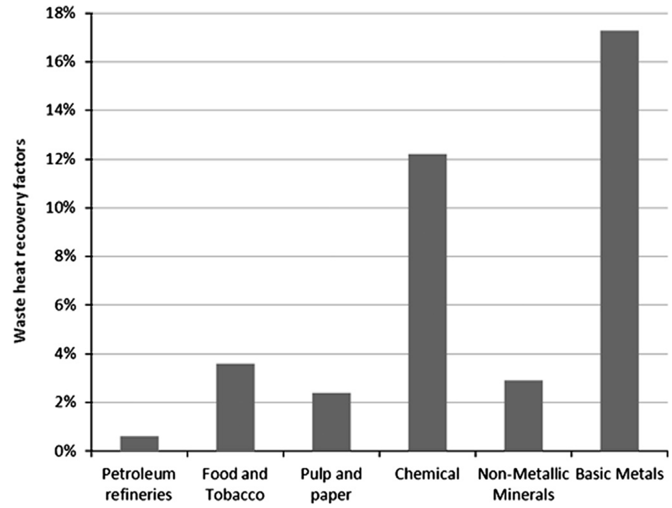

Fig. 4. Waste heat recovery factors in the Swedish industry, based on [32].

companies with more than 3 GWh equivalent of oil use per year that are closer to settlements were considered. To be considered as a settlement, the villages had to have at least 200 inhabitants and less than 200 m between neighboring houses. That way, 80 communities were investigated of which ten did not formerly have a district heating system. Within these communities, a total of 994 companies were considered. The developed key figures for each SNI sector were later applied to the total amount of used fuel in Sweden in the sector in question. Thus, a waste heat usage potential for district heating in Sweden was found to be 9.5 TWh. To develop these figures data from the government agency SCB (Statistics Sweden) or, when no data were available, empiric values from the Swedish district heating association were used. Since the developed data are based on companies and then transferred to the whole of Sweden, this approach is considered a combined bottom-up/top-down approach. The investigated potential is a technical potential, focused on district heating, without considering return of investment.

3.3. Interpretation of results

For all of the above-mentioned studies, there are two possible desired output parameters: they have to be distinguished between waste heat quantities on the one hand and percentage or share of waste heat from a certain input energy on the other hand. Quantity is important, if the focus is on possible market shares or potentials of technologies using waste heat. The share of the waste heat in comparison to the input energy is important to identify efficiency improvement potentials of sectors. It also gives a hint about which sectors to focus on with waste heat technologies and research. Shares are usually transferable from one region to another as long as the industrial structure is similar. Quantity on the other hand is bound to the investigated area and cannot be transferred to different areas. Nevertheless, there are certain similarities for different regions.

McKenna et al. [26] and Hammond et al. [29] considered the UK: the largest heat recovery potentials were found in the iron and steel sector as well as the chemical sector. Those are followed by the aluminum sector, cement, lime and glass. Werschy [39] received similar results for Germany: the largest heat recovery potential was identified in steel, non-iron metals, heat treatment, and glass and ceramic production.

Blesl et al. [25] also found the largest recovery potential in the metal production and processing industries, glass ceramics and non-metallic mineral processing, but also pulp and paper

Table 3
Comparison of the investigated studies.

Approach		Region and scope of study	Year of publication	References
Bottom-up survey	Questionnaire	Norway, 4 waste incineration plants and 72 companies	2009	[14]
	Mandatory reports	Basque country (Spain), 260 companies from 10 industrial sectors	1997	[16]
		Basque country (Spain), 290 companies from 10 industrial sectors	1998	[17]
	Online waste heat platforms	Thuringia (Germany)	2013	[18]
		Bavaria (Germany)	2011	[19]
		Saxony (Germany)	2011	[20]
		Netherlands	2009	[21]
Estimations	Bottom-up estimation	US, 15 manufacturing sectors plus mining	2004	[22]
		US	1994	[23]
		Baden-Württemberg (Germany), based on 4 investigated towns	2008	[11]
		Baden-Württemberg (Germany), estimations for different sectors based on case studies and aggregated to region	2012	[25]
		UK, 60% energy use from industry and 90% energy intensive sectors	2009, 2010	[26,27]
		UK, preceeding work for studies [26],[27], [29]	2001	[28]
		UK, 425 sites from the manu facturing sector	2012	[29]
	Top-down estimation	Germany, estimation based on energy factors form different studies	2010	[8]
		UK, process industry based on figures derived for the US	2012	[30]
		Europe, 32 states investigated using key figures derived in Sweden	2006	[34]
		Germany, expert estimation for German Industry	2001	[36]
	Combined top-down and bottom-up	North Rhine-Westphalia(Germany), key figures based on Duisburg, extrapolated to region	2002	[37]
		Sweden, 994 companies in 80 different communities investigated for key figures, than extrapolated to Sweden	2002, 2009	[35,38]

production, even though they investigated in a different area: Baden-Württemberg, a federal state in Germany (Fig. 3).

These similarities can be explained if the share of waste heat per unit input energy is taken into account. Fig. 4 shows factors derived from different industrial sectors in a Swedish study in 2003 [32].

The former sectors (basic metals, chemicals, non-metallic minerals, etc.) release a lot of their input energy as excess energy. So whenever these sectors are present in an area, they are bound to have a significant share of the industrial waste heat quantity.

Finally, Table 3 shows a summary of the 22 studies previously investigated, categorized according to the new classification proposed by the authors. In this summary, the region and the scope of the studies are listed with the year of publication of the study. In the case of the online waste heat platforms, the creation year of the platform is shown. According to the data acquisition, more estimations than bottom-up surveys have been found. Generally estimations are more precise, but they are also more time-consuming to obtain. Considering the approach, twice as many cases of bottom-up estimations than of top-down estimations are found.

Notice that this is a new research area and therefore the number of references is limited. This is also proven by the fact that some researchers reach back for studies as far as 1994 to estimate present day waste heat potentials although the infrastructure, production efficiency and methods have obviously changed in the past 20 years or more.

4. Conclusions

In this paper waste heat from industrial processes released as exhaust gas or exhaust air are considered, not including heat from combined heat and power plants. For quantifying this waste heat, it has to be distinguished as theoretical, technical or economic potential. In addition, multiple obstacles to use waste heat, which are also presented in this document, have to be considered.

Different methods to estimate the waste heat potential of regions have been presented and categorized according to the study scale, data collection and chosen approach. Using this new classification proposed by the authors, more than 30 studies have been categorized.

A wide variety of methods exists to estimate the waste heat potential. They mostly depend on the available data. Since for a lot of countries no country-specific data are available, many studies apply key figures from other countries. Within the European Union, a common definition of the industrial sectors is used. Yet, when leaving the European Union special attention has to be paid to the definition and boundaries of the sectors. Due to the different data bases in the different countries, a direct comparison of the different methods has so far not been possible. This lack of data is a very huge obstacle to the quantification and usage of the industrial waste heat. Also there is a need for a meta-analysis of the different study results for the same region.

Acknowledgments

Sarah Brückner would like to thank Stiftung der Deutschen Wirtschaft for her research fellowship. Laia Miró would like to thank the Spanish Government for her research fellowship (BES-2012-051861). The work was partially funded by BMWi Federal Ministry for Economic Affairs and Energy, Germany (Project FKZ 0327383B Mobile Sorption Heat Storage) and the Spanish Government (Project ENE2011-22722). The authors would also like to thank the Catalan Government for the quality accreditation given to their Research group GREA (2009 SGR 534).

References

[1] U.S. Energy Information Administration. International energy outlook; July 2013.
[2] De Beer J, Worrel E, Blok K. Long-term energy efficiency improvements in the paper and board industry. Energy 1998;23:21–42.
[3] Fleiter T, Fehrenbach D, Worrell E, Eichhammer W. Energy efficiency in the German pulp and paper industry: a model-based assessment of saving potentials. Energy 2012;40:84–99.
[4] Dittmar L, Schaefer M. Electricity demand modeling of German data centers: dealing with uncertainties. Schriftenreihe IZE; 2009.
[5] Neelis M, Patel M, Blok K, Haije W, Bach P. Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes. Energy 2007;32:1104–23.

[6] Egeskog A, Hansson J, Berndes G, Werner S. Co-generation of biofuels for transportation and heat for district heating systems—an assessment of the national possibilities in the EU. Energ Policy 2009;37:5260–72.
[7] Energieeffiziente Industrieofen Bine Informationsdienst; 2000.
[8] Pehnt M, Boedekery J, Arens M, Jochem E, Idrissora F. Die Nutzung industrieller Abwärme-technisch-wirtschaftliche Potenziale und energiepolitische Umsetzung Wissenschaftliche Begleitforschung zu uebergreifenden technischen, oekologischen, oekonomischen und strategischen Aspekten des nationalen Teils der Klimaschutzinitiative FKZ 03KSW016A und B; 2010.
[9] Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds). IPCC Fourth Assessment Q4 Report: Climate Change. Working Group III: Mitigation of Climate Change. Cambridge, United Kingdom; New York, NY, USA: Cambridge University Press; 2007.
[10] Roth H, Lucas K, Solfrian W, Rebstock F. Die Nutzung industrieller Abwärme zur Fernwärmeversorgung – Analyse der Hemmnisse für die Nutzung industrieller Abwärme zur Fernwärmeversorgung. Berlin: Umweltbundesamt; 1996.
[11] Blesl M, Kempe S, Ohl M, Fahl U, Konig A, Jenssen T, Eltrop L. Wärmeatlas Baden-Württemberg: Erstellung eines Leitfadens und Umsetzung für Modellregionen, Forschungsbericht, FZKA-BWPLUS; 2008.
[12] International Energy Agency, Industrial Energy-related Technologies and Systems. Industrial excess heat recovery technologies & applications; 2010.
[13] Mlirtensson A. Energy efficiency improvement by measurement and control, a case study of reheating furnaces in the steel industry. In: Proceedings from the 14th national industrial energy technology conference. Houston, TX; April 22–23, 1992.
[14] Enova. Utnyttelse av spillvarme fra norsk industry – en potensialstudie; 2009.
[15] Enova SF. 〈http://www.enova.no/about-enova/about-enova/our-history-and-our-mission/259/378/〉 [accessed 20.08.13].
[16] Bonilla JJ, Blanco JM, Lopez L, Sala JM. Technological recovery potential of waste heat in the industry of the Basque country. Appl Therm Eng 1997;3:283–8.
[17] Lopez L, Blanco JM, Bonilla JJ, Baeza S, Sala JM. Determination of energy and exergy of waste heat in the industry of the Basque country. Appl Therm Eng 1998;3:187–97.
[18] Thüringer Energie-und GreenTech-Agentur. 〈http://www.thega.de〉 [accessed 24.10.13].
[19] Energie-Atlas Bayern 2.0. 〈http://geoportal.bayern.de/energieatlas-karten〉 [accessed 24.10.13].
[20] Wärmeatlas Sachsen. 〈http://www.saena.de/projekte/waermeatlas.html〉 [accessed 24.10.13].
[21] Agentschap NL. 〈http://www.warmteatlas.nl〉 [accessed 24.10.13].
[22] Energetics, Incorporated. Energy use, loss and opportunities analysis: U.S. manufacturing & mining; 2004.
[23] Institution of Electrical Engineers. Profiting from low-grade heat: thermodynamic cycles for low-temperature heat sources. United Kingdom: Crook AW (ed) ; 1994.
[24] U.S. Department of Energy. Industrial Technologies Program, Waste heat recovery: technology and opportunities in U.S. Industry; 2008.
[25] Blesl M, Ohl M, Fahl U. Ganzheitliche Bewertung innovativer mobiler thermischer Energiespeicherkonzepte für Baden-Württemberg auf Basis branchen-und betriebsspezifischer Wärmebedarfsstrukturen Programm Lebensgrundlage Umwelt und ihre Sicherung (BWPLUS), durchgeführt vom Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) Universität Stuttgart; 2011.
[26] McKenna RC, Norman JB. Spatial modeling of industrial heat loads and recovery potentials in the UK. Energy Policy 2010;38:5878–91.
[27] McKenna RC. Industrial energy efficiency, Interdisciplinary perspectives on the thermodynamic, technical and economic constraints. University of Bath, Department of Mechanical Engineering; 2009. 〈http://opus.bath.ac.uk/18066/1/Industrial_Energy_Efficiency_McKenna_030809.pdf〉 [accessed 27.05.2014].
[28] Hammond G, Stapleton A. Exergy analysis of the United Kingdom energy system. J Power Energy 2001;215:141–62.
[29] Hammond GP, Norman JB. Heat recovery opportunities in UK manufacturing. In: Proceedings of the International Conference on Applied Energy (ICAE 2012). Suzhou, China; July 5–8, 2012.
[30] Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. Appl Energy 2012;89:3–20.
[31] Ecoheatcool work package 1. The European heat market. Final report; 2006.
[32] Werner S. Ecoheatcool - Possibilities with more district heating in Europe WP4. Euroheat & Power; 2006. 〈http://www.euroheat.org/files/filer/ecoheatcool/documents/Ecoheatcool_WP4_Web.pdf〉 [accessed 27.05.2014].
[33] Euroheat and power. The international association for district heating, district cooling and combined heat and power. 〈http://www.euroheat.org/ecoheatcool〉 [accessed 23.10.13].
[34] AGFW. Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. 〈http://www.agfw.de/europa-und-internationales/euroheat-power/〉 [accessed 20.8.13].
[35] Land A.L., Feldhusen Tvärne H.,A. Cronholm L.A.,Sundlof C. INDUSTRIELL SPILLVÄRME – Processer och potentialer. Svenska Fjärrvärmeforeningens Service AB; 2002.
[36] Glatzel WD, Langniß O, Pehnt M. Energie im Wandel: Politik, Technik und Szenarien einer nachhaltigen Energiewirtschaft Abwärme – die vergessene Eigenenergie: Ein Blick zurück und in die Zukunft. Berlin Heidelberg New York: Springer-Verlag; 2001; 151–64.
[37] Kattenstein T, Drath T, Ziolek A, Unger H, Wagner HJ. Validierung und kommunale Disaggregierung des Expertensystems HERAKLES. Abschlussbericht: Ruhr-Universität Bochum; 2002.
[38] Cronholm L, Gronkvist S, Saxe M. Spillvärme fran industrier – och värmeatervinning fran lokaler. Svensk Fyärrvärme; 2009 〈http://www.svenskfjarrvarme.se/Global/FJ%C3%84RRSYN/Rapporter%20och%20resultatblad/Rapporter%20omv%C3%A4rld/2009/Spillv%C3%A4rme%20fr%C3%A5n%20industrier%20och%20lokaler%20.pdf〉[accessed 27.05.2014]..
[39] Werschy M. Technologierecherche Abwärmenutzung DBI Gas-und Umwelttechnik GmbH für die Sächsische Energieagentur – SAENA GmbH; 2010.